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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Variation in Radiation Dose Rate with Altitude and Shielding Thickness at Orbits Near Synchronous

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ABSTRACT

To assist in preliminary mission planning for AAP high altitude, manned earth orbit flights, the variations in radiation dose rate accompanying a change in spacecraft shielding or change in spacecraft orbit altitude are discussed. Using the description of the electron flux and spectrum at synchronous altitude ($6.6R_e$) developed by J. I. Vette plus several simplifying assumptions, the change in skin dose rate and bremsstrahlung dose rate is obtained as a function of shielding thickness and hardness of the energy spectrum of the trapped electrons. Based on an assumed simple relation between the hardness of the spectrum and the distance from the center of the earth to the point of interest, the dose rate is related to the orbital altitude.

At synchronous altitude approximately one order of magnitude reduction in skin dose rate is obtained for each additional 0.2 gm/cm^2 of shielding provided to the astronaut. By increasing the orbital altitude from $6.6R_e$ to $7.1R_e$, the bremsstrahlung dose rate is decreased 50% and the skin dose rate an order of magnitude. It is also estimated that at an orbital altitude of $7.4R_e$ inclined 30°, the deep body dose from the trapped electrons equals the dose from general galactic cosmic ray background.

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SUBJECT: Variation in Radiation Dose Rate with Altitude and Shielding Thickness at Orbits Near Synchronous - Case 600-1

DATE: May 23, 1967

FROM: T. C. Tweedie, Jr.

TM-67-1021-1

TECHNICAL MEMORANDUM

Introduction

The Apollo Applications Program (AAP) is currently considering manned synchronous earth orbit missions for 1970. These missions have objectives similar to the first four low altitude AAP missions (i.e., long duration and astronomy) but operate in a different radiation environment. Low altitude earth orbit missions operate generally on the lower edge of the inner belt of trapped protons and electrons; a synchronous orbit, however, passes through the outer regions of the outer zone of trapped electrons. To assist in preliminary mission planning for flights to synchronous altitude, the variations in dose rate accompanying a small change in orbit altitude or a change in spacecraft shielding is discussed. Estimates of the radiation dose that a man receives in the region of synchronous altitude have a wide dispersion because of limited measured data on the nature of the electron flux and energy spectrum; however, through a series of approximations, an estimate of the variation in dose rate with shielding thickness, electron energy spectrum and altitude (near synchronous) is obtained. The results must be interpreted in light of the assumptions and should not be considered to represent a final determination of the radiation hazard.

Radiation at Synchronous Altitude

There are three contributions to the radiation hazard to manned space flight at altitudes near earth synchronous: galactic cosmic rays, solar particle events, and the particles trapped in the earth's magnetic field. Galactic cosmic rays, which are high energy, relatively low flux particles, are part of the general space environment. The contribution of cosmic rays to the radiation hazard is approximately constant varying only by a factor of three over the 11 year solar cycle. Solar eruptions which produce energetic particles also vary in frequency of occurrence over the solar cycle. The solar particles, primarily protons and alpha particles, can produce a serious radiation hazard to manned space flight. Because of the severity of some solar particle events, the amount of special shielding protection required must be examined separately.

Charged particles trapped in the earth's magnetic field constitute a natural radiation hazard to manned spacecraft. For spacecraft orbiting near synchronous altitude (6.6 earth radii), the primary radiation hazard is caused by the trapped electrons; trapped protons because of their low flux do not significantly contribute to this high altitude radiation climate. The best available published information on the trapped electrons is that developed by J. I. Vette[1] from an analysis of the data from Explorer 6, Explorer 12, Explorer 14, Imp A, OGO A and ERS-17 satellites.* Based on the limited data which he examined, Vette derived an empirical description of the electron environment at synchronous orbit distances which included a complex relation between the energy spectrum, diurnal change and magnetic field variations. Vette found that a good fit for the observed energy spectrum of the electrons was of the form $\exp(-E/E_o)$ where E_o is a parameter used to reduce the measured data to an analytical form. Expressed in energy units E_o is a measure of the energetic distributions of electrons in a given flux. When the number of electrons with energy greater than E are plotted as a function of E on semi-log paper, E_o^{-1} is the slope of the line. Large fluxes of electrons with high energy content are called hard.

To examine the dependence of energy spectrum and shielding thickness on dose rate, several simplifying assumptions to the Vette model are made. To account for the magnetic latitude dependence on electron flux and spectrum for a particular orbital altitude, Vette included a term $(B/B_o)^{-0.625}$ where B_o is the equatorial value of B on the line of force and B is the latitude dependent magnetic field.[2] By considering equatorial orbits only, $B/B_o = 1$ and the latitude dependence is removed.

Diurnal variations in electron flux (about an order of magnitude over a 24 hour period) are seen in the representative curves shown in Figure 1. This variation included in the

*The ATS-B satellite, launched into equatorial synchronous orbit over the Pacific in Dec. 1966, has radiation measuring instruments on board but this data has not been reduced to usable form. The earliest estimates for availability of this data is late summer 1967.

Vette model is smoothed by assuming a constant time weighted average flux. Because of solar activity, the electron flux may change another one to two orders of magnitude. It is assumed that the time in orbit is large compared to the frequency of solar events and their relaxation time so that an average dose rate would be representative of the actual situation.

Radiation Effects

The total radiation dose that an astronaut receives is commonly described by two terms: skin dose and deep body dose. Skin dose results when energetic particles pass through any protective shielding around the astronaut, impact on his skin, and then rapidly lose kinetic energy over a short penetration depth into the skin. Radiation that penetrates deeply into the human body and is quite injurious to the internal organs and the blood forming centers is called deep body dose. The current radiation dosages which are acceptable by MSC for planning purposes[3] for a 60 day mission are:

	Dose Rate	Total
Skin	2.5 rem/day*	150 rem
Deep Body	0.5 rem/day	30 rem

The trapped electrons at synchronous altitude can produce both a skin dose and a deep body dose of radiation to an astronaut. A fraction of the electrons which are intercepted by the spacecraft pass through the spacecraft walls and any protective shield and deposit their energy in the skin tissue of the astronaut. The skin dose received is dependent on the incident flux of electrons, their energy, and the amount of shielding afforded the astronaut.

As the energetic electrons pass through the walls of the spacecraft and any other material, they radiate energy as they are deflected by coulomb interactions in the materials. A portion of the kinetic energy lost by the electrons in decelerating is converted into penetrating X-rays (bremsstrahlung) which impact the astronaut and give him a deep body dose of radiation. The amount of bremsstrahlung produced by the electrons is relatively insensitive to the thickness of the material but rather dependent on the atomic number of the material (the number of protons in a nucleus and hence effectiveness in deflecting the incident electrons) and the energy of the incident electrons.

*One rem (roentgen equivalent man) is the unit of radiation that produces tissue damage in man.

Radiation Dose

Skin Dose

The skin dose rate produced by the primary electrons is given by the product of the energy dependent electron flux N(E) incident on the spacecraft, the transmission of the electrons T(E,X) through the spacecraft walls of thickness X and the rate of energy loss of the electrons in the skin $\frac{dE}{dX}$. Over the energy range 0.35 to 10 Mev $\frac{dE}{dX}$ is approximately constant. The expression for skin dose is written as

$$D_{SK} = K \int_0^\infty T(E,X)\ N(E)\ dE$$

where K incorporates $\frac{dE}{dX}$ and the conversion between the energetic electron flux incident on the skin and dose rate. Based on calculations by Berger and Seltzer,[4] R. H. Hilberg has derived an empirical transmission function

$$T(EX) = \exp(1.06X^2E^{-2} - 29.5X^3E^{-3})$$

The energy dependent electron flux is given by

$$N = N_o e^{-E/E_o}$$

Substituting

$$D_{SK} = KN_o \int_0^\infty \exp(1.06X^2E^{-2} - 29.5X^3E^{-3} - EE_o{}^{-1})dE$$

The skin dose rate is thus a complex function involving X, the thickness of the shielding in gm/cm^2, and E_o, the hardness of the incident electron energy spectrum. The integral is evaluated by a numerical computer program for thicknesses ranging from zero to 1 gm/cm^2 as E_o is decreased in discrete steps from an initial value of 0.215 Mev* to 0.12 Mev.

*This value of E_o was used by Vette as characteristic of the electron energy spectrum at synchronous equatorial orbit.

To demonstrate the variation in skin dose rate with X and E_o, the numerical results, presented in Figure 2, are normalized to zero shielding and an E_o = 0.215 Mev. N_o is assumed to remain constant for all values of E_o. From the curves in Figure 2 it can be seen that the skin dose rate decreases by about an order of magnitude for every increase of 0.2 gm/cm^2 of shielding and that as the energy spectrum of the electrons is softened (E_o decreasing), material shielding becomes more effective. For a given shield thickness of 1.0 gm/cm^2, a change of E_o from 0.215 Mev to 0.12 Mev results in about three orders of magnitude reduction in dose rate, while the dose rate behind a shield of 0.4 gm/cm^2 changes only about a factor of 40 over the same range of E_o.

The variation in radiation protection afforded by various spacecraft modules is given in Table I:

Table I

	CM	LM	MDA	S-IVB	EVA (Suit)
Shield Thickness gm/cm^2	2.4	0.2*	0.55	0.75	0.1

Bremsstrahlung Dose

The bremsstrahlung dose rate, D_B, is given by the product of the number of electrons with energy E, times their energy, and the efficiency e of bremsstrahlung production for materials of atomic number Z, integrated over all electron energies.

Thus

$$D_B = K_1 \int_0^\infty eE\ N(E)\ dE$$

K_1 - numerical constant for conversion to dose rate

$$e = 5 \times 10^{-4} ZE \quad 5$$

$$N = N_o e^{-E/E_o}$$

*Approximately 25% of the solid angle as seen by an observer inside the LM is shielded by 0.16 to 0.20 gm/cm^2. The other 75% has shielding approximately 1 gm/cm^2.

Substituting

$$D_B = K_1 \int_0^\infty 5 \times 10^{-4} ZE^2 N_o e^{-E/E_o} dE$$

$$= K_1 5 \times 10^{-4} ZN_o (2E_o{}^3)$$

$$D_B = K_1 10^{-3} ZN_o E_o{}^3$$

The deep body dose rate is thus strongly dependent on E_o, the hardness of the energy spectrum and linearly dependent on the electron flux and the atomic number of the shielding material. Additional material shielding up to several gm/cm^2 will not significantly reduce the radiation dose.*

Variation in Radiation Dose with Altitude

The mechanism by which protons and electrons are contained in the region about synchronous altitude is dependent on the structure and strength of the earth's magnetic field. Several descriptions of the earth's magnetic field involve expansions of spherical harmonics, but a more convenient model is an offset dipole representation. At large distances from the center of the earth, the dipole field would have a simple R^{-3} dependence, but in fact the field lines are distorted by a solar wind pressure thus creating an anisotropy in the magnetic field. Since the Van Allen region** for stable trapping of particles is commonly assumed to extend out to about 8 R_e, which implies a reasonably ordered magnetic field in this region, relationships between trapped particle flux and field strength can be estimated. Analysis of measurements of proton energies at distances out to slightly greater than 6 R_e indicates that their energy spectrum can be represented by the form $\exp(-E/E_o)$ and that E_o varies as R^{-3}. The limited data reported by Vette for trapped electrons also appears to show a proportionality between E_o and R^{-3}. Thus the proportionality between E_o and R^{-3} appears useful for preliminary estimates of electron spectrum variation (and hence dose) with altitude over small distances for the region near synchronous and out to about 8 R_e.

*About 20 gm/cm^2 are required to reduce the deep dose by an order of magnitude.

**Region in which particles execute motions between mirror points and drift completely around the earth.

Thus

$$E_o = C \frac{1}{R^3}$$

C - constant of proportionality

and

$$\frac{dE_o}{E_o} = -3 \frac{dR}{R}$$

A 10% change in orbital radius (dR) results in a 30% change in E_o. The change in E_o can be related to the skin dose rate through the curves of Figure 2 or to the bremsstrahlung dose rate through the equations developed above.

To reduce the skin dose rate an order of magnitude behind a spacecraft shielding thickness of 0.8 gm/cm^2 in a region at synchronous altitude (6.6 R_e) in which E_o = 0.215 Mev, it is necessary either to increase the shielding or to increase the orbital altitude. If it is desired to keep the orbital altitude fixed at 6.6 R_e, radiation protection can be increased by adding more shielding to the spacecraft. To decrease the skin dose rate an order of magnitude, an additional 0.2 gm/cm^2 must be added. For a volume the size of the S-IVB Orbital Workshop, additional shielding of 0.2 gm/cm^2 distributed over the exposed surface area would result in an additional weight of about 400 lbs. Since the efficiency of bremsstrahlung production is proportional to the atomic number of the shielding material, a low Z material should be used as the shield.

To accomplish the same order of magnitude reduction in skin dose rate by increasing the orbital altitude, it is necessary to reach a region in which E_o = 0.17 Mev (from Figure 2). The orbital altitude at which E_o = 0.17 Mev is 7.1 R_e (as determined from $E_o \alpha \frac{1}{R^3}$) or an altitude increase of about 1700 nm.

The corresponding fractional decrease in the bremsstrahlung dose by the decrease in E_o from 0.215 Mev to 0.17 Mev is

$$\frac{dD_B}{D_B} = 0.49$$

Thus by increasing the orbital altitude about 1700 nm, the radiation skin dose is reduced an order of magnitude and the bremsstrahlung deep body dose is reduced about 50%. However, by flying in an orbit other than 6.6 R_e, the synchronous nature of the orbit with respect to a point on the earth is lost. In a orbit at 7.1 R_e the orbital period is 2.7 hours greater than the 24-hour period at 6.6 R_e.

Long Duration Mission

In planning a long duration, high altitude, earth orbit mission, it is desirable to fly in a region of space in which the radiation dose received by the astronauts is a minimum. As noted, the skin dose can be reduced by additional shielding while the deep dose from the bremsstrahlung electrons and the galactic cosmic rays is relatively insensitive to shielding. Since a lower limit of radiation dose can be set by the relatively constant cosmic ray background, it is inefficient to try to reduce the electron bremsstrahlung deep dose much below the cosmic ray dose. By equating the expression for bremsstrahlung dose rate with an average cosmic ray dose rate, the equivalent high altitude trapped radiation environment can be found.

$$D_B = D_{galactic}$$

$$\frac{1}{6} \times 10^{-8} ZN_oE^3 = 1.35 \times 10^{-3} \text{ rem/hr}$$ [6]

For aluminum shielding Z = 13

$$N_oE_o{}^3 = 5.5 \times 10^4$$

N_o, the differential electron flux, is considered approximately constant in the radial direction over small distances about 6.6 R_e but decreases with latitude due to the latitude dependence of the magnetic field. The expression is evaluated and the results shown in Table II for equatorial orbits and 30° inclination orbits.

Table II

Inclination	$N_o \dfrac{\text{electrons}}{\text{Mev cm}^2\text{ sec}}$	E_o(Mev)
0°	2×10^8	0.065
30°	1.67×10^7	0.15

Using the $1/R^3$ dependence to determine the altitude corresponding to $E_o = 0.065$ leads to an orbital altitude beyond 8 R_e and is not an allowed solution within the scope of the model assumed. An $E_o = 0.15$ is equivalent to a 7.4 R_e orbit. At this orbital altitude, inclined 30°, the bremsstrahlung dose and the galactic cosmic ray dose are equal, and an astronaut would receive about 2.7×10^{-3} rem/hr (0.065 rem/day) which is substantially below the 0.5 rem/day acceptable for 60 day mission plans. However, if high altitude missions of one year or more in duration are to be considered, then this low dose rate may be required.

Conclusions

Using the description of the electron flux and spectrum at synchronous altitude (6.6 R_e) developed by J. I. Vette plus several simplifying assumptions, the change in skin dose rate and bremsstrahlung dose rate is obtained as a function of shielding thickness and hardness of the electron energy spectrum. Based on an assumed simple relation between the hardness of the spectrum and the distance from the center of the earth to the point of interest, the dose rate is related to the orbital altitude.

At synchronous altitude, approximately one order of magnitude reduction in skin dose rate is obtained for each additional 0.2 gm/cm^2 of shielding provided to the astronaut. Material shielding affords relatively little protection against bremsstrahlung. By increasing the orbital altitude from 6.6 R_e to 7.1 R_e, the bremsstrahlung dose rate is decreased 50% and the skin dose rate an order of magnitude. It is also estimated that at an orbital altitude of 7.4 R_e inclined 30°, the deep body dose from the trapped electrons equals the dose from general galactic cosmic ray background.

Acknowledgement

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T. C. Tweedie Jr.

1021-TCT-bap T. C. Tweedie, Jr.

Attached:
Figures 1 and 2

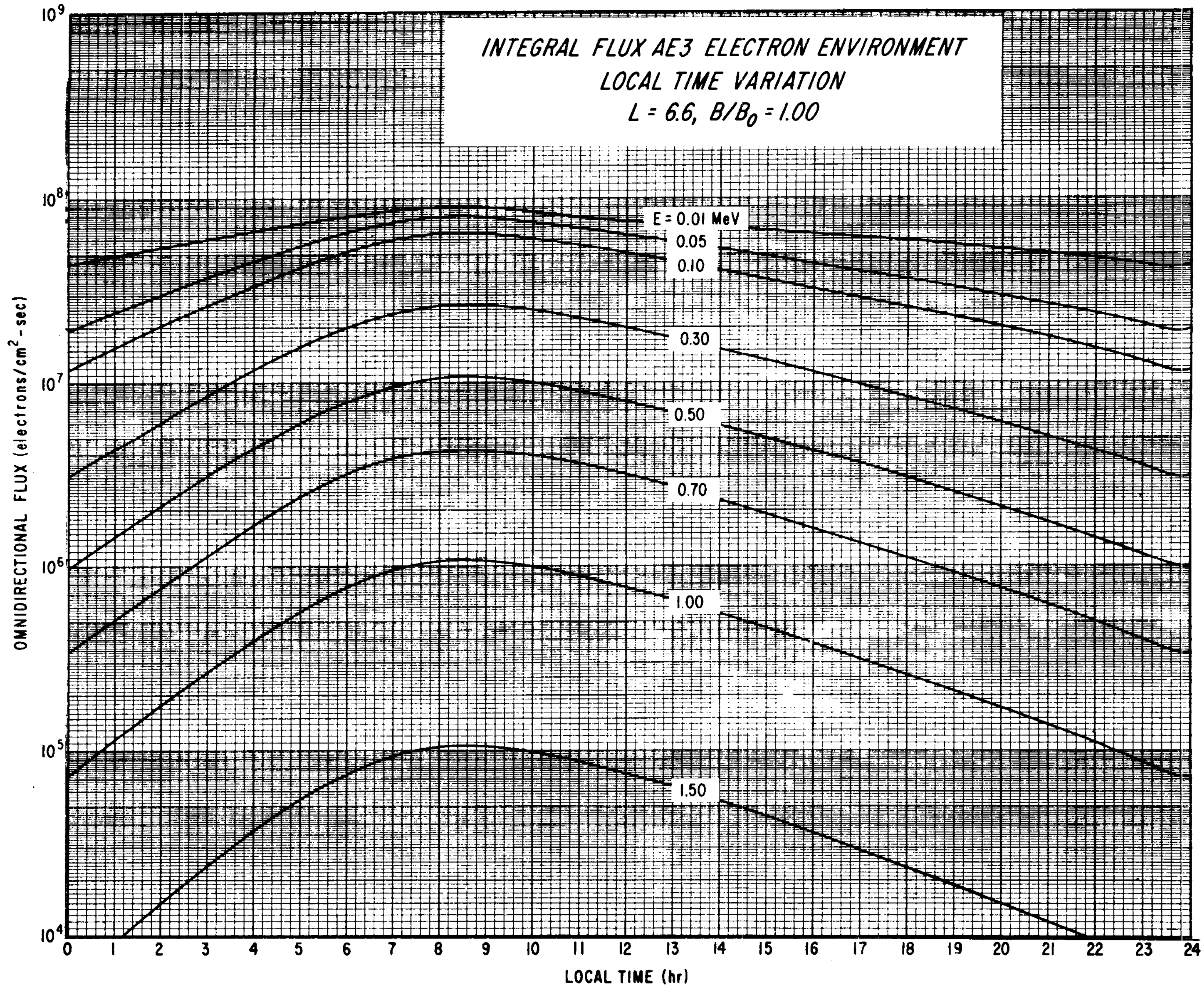
INTEGRAL FLUX AE3 ELECTRON ENVIRONMENT
LOCAL TIME VARIATION
L = 6.6, B/B0 = 1.00
E = 0.01 MeV
0.05
0.10
0.30
0.50
0.70
1.00
1.50
OMNIDIRECTIONAL FLUX (electrons/cm2-sec)
LOCAL TIME (hr)

FIGURE 1

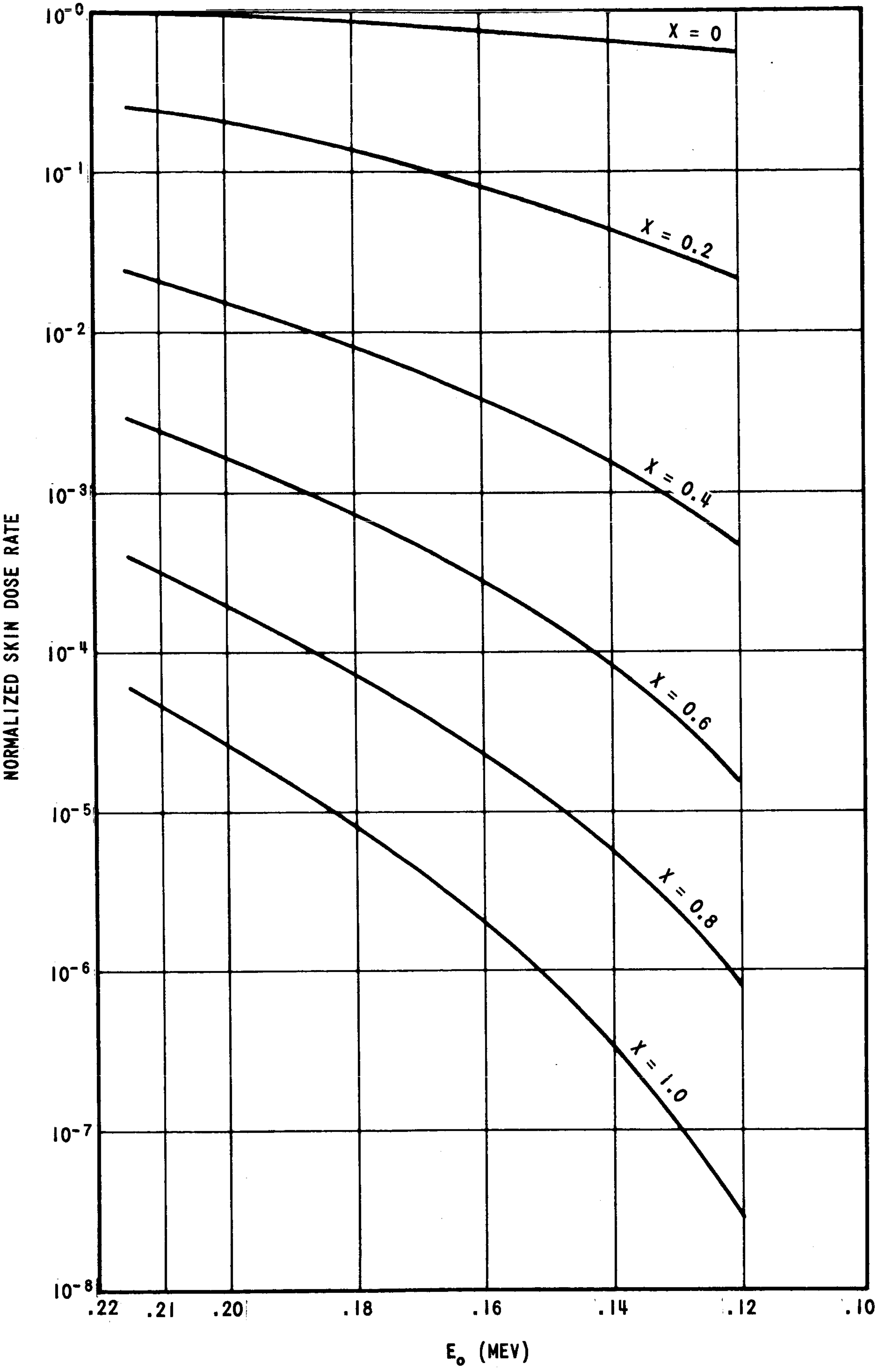

FIGURE 2 - NORMALIZED SKIN DOSE RATE VS. E_o FOR VARIOUS SHIELDING THICKNESSES IN gm/cm^2

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